

**Drivers of Atlantic Sturgeon
Time of Arrival and Residency in the
Delaware Wind Energy Lease Area**

By

Ella McNeece

A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the
requirements for the degree of Bachelor of Science in Marine Science with Distinction

Spring 2026

© 2026 Ella McNeece

All Rights Reserved

Drivers of Atlantic Sturgeon
Time of Arrival and Residency in the
Delaware Wind Energy Lease Area

by

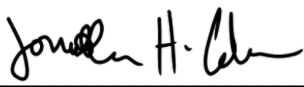
Ella McNeece

Approved: 

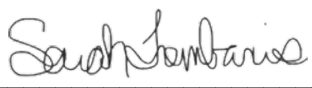
Matthew Oliver , Ph.D
Professor in charge of thesis on behalf of the Advisory Committee

Approved: 

Edward Hale, Ph.D
Committee member from the Department of Marine Science and Policy

Approved: 

Jonathan Cohen, Ph.D
Committee member from the Board of Senior Thesis Readers

Approved: 

Sarah Trembanis , Ph.D.
Chair of the University Committee on Student and Faculty Honors

ACKNOWLEDGEMENTS

This thesis could not have been completed without use of the acoustic telemetry data collected for the University of Delaware and Delaware State University study on the Delaware Wind Energy Lease Area. I am incredibly thankful to use the work of Danielle Haulsee, Matthew Oliver, and Dewayne Fox for this thesis. I have gained valuable data analytic skills that I hope to utilize throughout my own career.

Thank you to Matthew Oliver for taking me into his laboratory in my sophomore year. I am very grateful for all the work and opportunities that have been put into my academic career. This leads into how grateful I am to complete this senior thesis under the supervision and guidance of ORB Lab. The direction, instruction, and support given from Matthew Oliver, Yuleny Gomez Rodriguez, Caroline Wiernicki, Rebecca Walsh, Piper Priddy, Amy Duh, and Rachel Lazzaro is greatly appreciated and will not be forgotten. Their patience, excitement, and care towards my academic career was invaluable and helped me every step of the way. I was extremely lucky to grow as a scientist and as a person for over two years in this atmosphere.

A special thank you towards the rest of my committee: Edward Hale and Jonathan Cohen. The advice given towards this thesis (and life) was greatly appreciated. I'd like to express my gratitude towards these professors, where I learned a great deal about invertebrates, statistics, and sturgeon.

Finally, the support from my roommates, friends, parents, and family was what I needed to get through this long process. A special thank you to my grandparents, Grandpa and Grandma, along with my little brother, William McNeece, for being my biggest supporters. To Teagan Rudderow and Jack Goldman, thank you for being there when you were needed most.

TABLE OF CONTENTS

LIST OF FIGURES.....	v
ABSTRACT.....	vi
1 INTRODUCTION.....	1
1.1 The Atlantic Sturgeon in Delaware Bay.....	1
1.2 Movement Ecology.....	3
1.3 The Use of Wind Energy in the Atlantic Ocean.....	3
1.4 The Acoustic Telemetry Study Done in the Delaware Wind Energy Lease Area.....	5
2 METHODS.....	9
2.1 The BOEM Study on Atlantic Sturgeon Occurrence.....	9
2.2 The Senior Thesis Method.....	10
3 RESULTS.....	13
3.1 Hypothesis One - Arrival and Residence Times Between Male and Female Sturgeon.....	14
3.2 Hypothesis Two - Bottom Temperature with the Arrival of Male and Female Sturgeon.....	15
3.3 Hypothesis Three - Arrival and Residence between Male, Female, and Juvenile Sturgeon....	17
3.4 Hypothesis Four - Arrival and Residence Time of the Sturgeon's River of Origin.....	18
3.5 Hypothesis Five - Photoperiod with The Arrival of Each River of Origin.....	20
4 DISCUSSION.....	22
5 CONCLUSION.....	26
REFERENCES.....	27

LIST OF FIGURES

Figure 1. Picture of Atlantic Sturgeon During Tagging Efforts.....	2
Figure 2. Map of DE WEA.....	3
Figure 3. Bottom and Surface Temperature in the DE WEA.....	6
Figure 4. General Area of Release Location.....	11
Figure 5. Circular Plot of Arrival between Male and Female Atlantic Sturgeon.....	13
Figure 6. Boxplot of Residency Time Between Male and Female Atlantic Sturgeon.....	14
Figure 7. Boxplot of Bottom Temperature Upon Arrival Between Female and Male Atlantic Sturgeon.....	15
Figure 8. Circular plot of arrival between female, male, and unknown/juvenile Atlantic sturgeon.....	16
Figure 9. Boxplot of day of residency time between female, male, and unknown/juvenile Atlantic sturgeon.....	17
Figure 10. Circular plot of arrival between different release locations.....	18
Figure 11. Boxplot of residence times between different release locations.....	19
Figure 12. Boxplot of first photoperiod upon arrival by different release locations	21

ABSTRACT

The Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) is known to be a highly migratory endangered species that occurs in Delaware waters throughout the calendar year. An acoustic telemetry study was done by the University of Delaware and Delaware State University for the Bureau of Ocean and Energy Management (BOEM) to analyze Atlantic sturgeon occurrence in the Delaware Wind Energy Lease Area (DE WEA). From this study, the 2020 BOEM report concluded that bottom temperature was the most ecologically interpretable variable for Atlantic sturgeon occurrence in the DE WEA. It was also interpreted that the construction of the DE WEA should happen in the summer months, where Atlantic sturgeon occurrence is low. This conclusion was based on minimizing sturgeon mortality. This thesis utilized and based the hypotheses on the acoustic telemetry dataset collected for the 2020 report.

The purpose of this thesis was to find ecological drivers for the arrival and residency time of the Atlantic sturgeon in the DE WEA. In R Studio, multiple calculations and statistical tests were done to draw conclusions for the five main hypotheses. It was found that the sex of the Atlantic sturgeon was the only ecological variable to show statistical significance from the Watson Wheeler test ($P = 0.03635$) ($P < 0.05$). The females arrived earlier in the calendar year, having a median day of 304. While the males arrived later and had a median arrival on day 322. Individuals females were also found to have a longer residency period in the DE WEA, indicating more exposure to potential harm. This conclusion of sex being an ecological interpretable factor should be further used to explain predictors of Atlantic sturgeon in Delaware waters.

Chapter 1

INTRODUCTION

1.1 The Atlantic Sturgeon in Delaware Bay

The Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) have large-scale migration throughout the east coast of Canada and the United States. The movement of these organisms happens twice a year, with movement northward in the spring for spawning, and southward in the fall. During this migration, the sturgeon are at risk for fisheries bycatch, with the height of this action happening in the fall, winter, and spring (Breece 2018, Collins 2000). The Delaware River is utilized as a spawning ground, having increased sturgeon numbers on a periodic basis.

The Atlantic sturgeon population became endangered due the overexploitation of the Delaware Bay between 1890 - 1899. During this time, Delaware Bay comprised 75% of sturgeon harvest in the United States. This was coined the gold-rush era for the caviar industry and the Delaware Bay supported the largest caviar capital in the United States (Mitchell 2025, Smith 1985, Limberg and Waldman 2009). From this phenomenon, the Delaware Bay sturgeon population was depleted, leading to a market crash in 1901 (Secor 1999). Since then, Atlantic sturgeon populations are at risk of extinction. However, efforts towards conservation have been put forth for five distinct population segments (DPSs) of Atlantic sturgeon: The New York Bight, Chesapeake, Carolina, South Atlantic, and Gulf of Main. The Endangered Species Act (ESA) listed 4/5 DPSs as endangered on April 6, 2012 (Breece, 2018). This was a step towards the population recovery, but the threat of extinction for the Atlantic sturgeon is still prominent.



Figure 1. Picture of Atlantic sturgeon during tagging efforts

The Atlantic sturgeon were caught, tagged, and photographed along with the needed measurements. Picture was taken from the BOEM report (Haulsee 2020)

The Delaware Bay is an estuary that has been known to support many of anadromous fish spawning populations, including the Atlantic sturgeon (Sullivan 2008). Adult Atlantic sturgeon will migrate from the Atlantic through the Delaware Bay to spawn in the Delaware River. Reaching maturity for Atlantic sturgeon differs between sex. Researchers estimate male Atlantic sturgeon are mature between 12 - 19 years, while females will reach maturity 16 - 24 years (DNREC, Daigle 2025). Although there is limited information towards the location and timing of Atlantic sturgeon reproductive behavior, it is known the Delaware River's salinity and substrate composition are suitable for spawning behavior. Atlantic sturgeon eggs require a salinity below 0.25 PSU, due to their salt intolerance. The eggs are highly adhesive requiring a hard substrate, such as coarse sand or hardpan clay (Breece 2013, Atlantic States Marine Fisheries Commission

2012). When these eggs hatch, these newly hatched sturgeon will remain within the freshwater area, slowly moving towards the ocean (Smith 1985, NOAA).

1.2 Movement Ecology

Movement ecology is necessary when understanding the behavior of different marine organisms. The four fundamental questions induce research within this specific field: why move, how to move, when to move, and where to move (Nathan 2008). Internal and external environmental factors heavily influence the movement of all organisms, especially marine species. These factors could span between reproductive behavior to temperature driven migration. Movement ecology is used in a span of different fields, specifically in policy and conservation (Cooke 2022). Understanding the movement of specific species is used in developing research plans and sustainability measures.

The movement ecology of the Atlantic sturgeon is still being studied, with papers published on the environmental drivers of their movement, especially in the Delaware Bay. It has been found that cold waters reduce Atlantic sturgeon residency and increased movement in the Delaware Bay (Breece 2018). Another study agrees with Breece's study with Atlantic sturgeon occurring in higher bottom temperatures, having occurrences in warmer near-shelf waters (Rothermel 2020). The concentration of Atlantic sturgeon are heightened at mouths of estuaries, which is where The Delaware Wind Energy Lease Area (DE WEA) is near, in late spring through fall.

1.3 The Use of Wind Energy in the Atlantic Ocean

The construction of wind farms in the Atlantic coastal ocean has begun. European countries have 43 wind farms with more than 948 wind turbines in the Atlantic ocean (Fisher et al 2010). There is more than 1,283.5 GW of total potential offshore wind in the Atlantic coastal

oceans. Putting this in perspective, 1 GW can supply between 250,000 - 300,000 on average in United States homes. In the Mid-Atlantic States, wind farms could generate \$200 billion in economic activity and create about an estimated 43,000 jobs. These jobs would be permanent and high paying for the employed Americans. While coal creates 667 MW per average size coal-powered plant (Energy Justice Network 2007). While wind farms are found throughout the United States, offshore wind farms have an increased electricity generation compared to wind farms on land due to the increased wind force (Musial and Ram 2010).

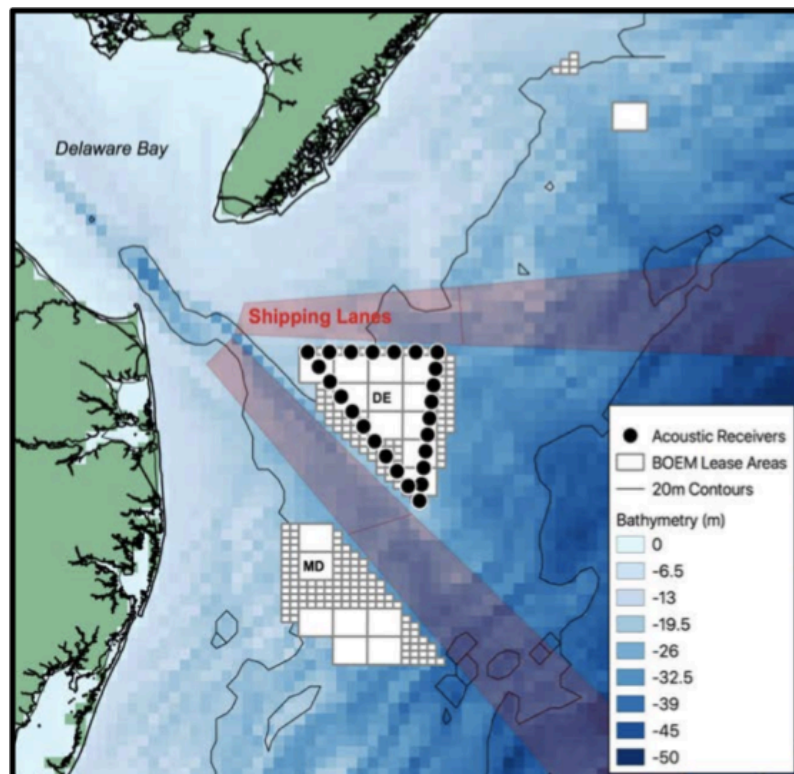


Figure 2. Map of DE WEA

Bathymetry map of the Delaware Wind Energy Lease Area from the 2020 report (Haulsee 2020). Each individual black dot is an acoustic receiver.

The Mid-Atlantic Bight has waters less than 60 m deep, thus a suitable environment for offshore wind energy technology (Musial and Ram 2010). The DE WEA is 11-23 miles east of Rehoboth Beach, fitting between two major shipping routes (Haulsee 2020) (**Figure 2**). The Atlantic Sturgeon, as mentioned above, has residency and movement within this coast and bay region (DNREC). The population of the Atlantic sturgeon is potentially threatened by construction of wind turbines in the DE WEA. Their movement, which happens periodically during the year, could put them in potential interaction and harm during the construction of these wind turbines. While the use and development of clean offshore wind energy is needed within the 21st century, the creation of these wind turbines is hazardous towards the organisms in the area of development.

1.4 The Acoustic Telemetry Study Done in the Delaware Wind Energy Lease Area

Acoustic telemetry is a common way for marine researchers to track animal behavior. There are two parts to this research method, active (sound emission) and passive (sound reception by the tag and decoding by the receiver) acoustic telemetry (SINAY 2024). These tags transmit a signal to a receiver on a mooring, boat, or other platform when in a range of contact. The receiver will collect time and the specific transmitter code for identification when in range of the transmitter. In 2017 - 2019, an acoustic telemetry study was done by the University of Delaware and Delaware State University for the Bureau of Ocean and Energy Management (BOEM). The study's main objective was to analyze Atlantic sturgeon occurrence in the DE WEA. This study also developed environmentally driven occurrence models of Atlantic sturgeon in the DE WEA. The researchers sought to find and provide the seasonal pattern of occurrence and habitat use of the Atlantic sturgeon, along with the underlying environmental factors that correlate with this occurrence (Haulsee 2020).

Once the study was completed, it was recommended that construction efforts in the DE WEA be done within the summer months to reduce the interaction with the Atlantic sturgeon. As for Atlantic sturgeon population behavior, the study suggested bottom temperature was an ecological factor for this endangered species occurrence. Predicting sturgeon presences was calculated in this study using generalized additive models (GAM). It was found a sturgeon predictor was bottom temperatures between 10 - 25°C. Since Atlantic sturgeon spend their time at the bottom of the seafloor, it makes sense to use bottom temperature as a predictor variable for their occurrence (Erickson 2011). However, more ecological factors that drive this species occurrence are still being tested by marine researchers. In contrast to the BOEM study that focused on Atlantic sturgeon occurrence, this thesis aims to predict common ecological factors (bottom temperature, sex, photoperiod, and river of origin) influencing Atlantic sturgeon arrival and residency time in the DE WEA. I will use the past acoustic telemetry data done for the 2020 BOEM report.

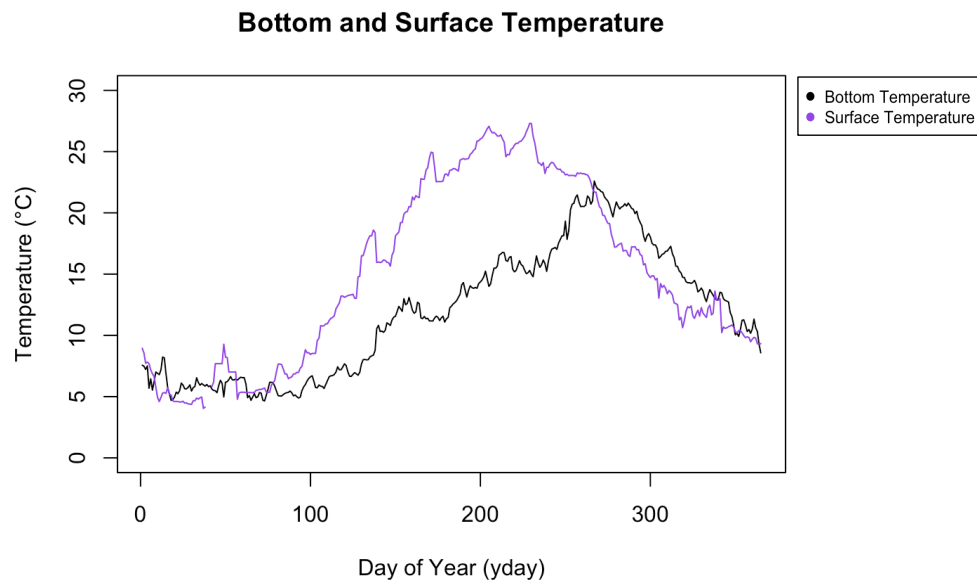


Figure 3. Bottom and Surface Temperature in the DE WEA

The time series shown above is surface and bottom temperature throughout the year in the Delaware Wind Energy Lease Area. Generated in R Studio and code aided by OpenAI.

1.5 Ecological Drivers of Arrival Time and Residence Time for the Atlantic Sturgeon

Between September 2024 and May 2026, I worked under the guidance of Dr. Oliver and the Ocean Exploration, Remote Sensing, and Biogeography Laboratory (ORB Lab) to analyze the cleaned data collected during Dr. Oliver's study. I set out to understand and test ecological variables to find drivers of Atlantic sturgeon arrival and residency time in the DE WEA. Atlantic sturgeon were occurring throughout the year in this area, however, the drivers of their arrival day and residence time in this region is unknown. These two key components to migration are what puts sturgeon at risk during the DE WEA construction. If many fish are moving quickly through the system, then exposure to construction disturbances will be low. However, if individual fish are staying for extended periods, then exposure of construction disturbances could be significant on the individual level.

Migratory behavior is often driven by a range of ecological factors and processes, and is found in many species, from terrestrial to marine. It is defined as a seasonal round trip between two or more locations of an organism (Shaw 2016). Fish are commonly defined to have three types of migration behaviors: diadromous, potomadromous, and oceanodromous. As mentioned above, Atlantic sturgeon are anadromous, a primary type of diadromous fish. Anadromous migration is known to be driven by breeding.

An ecological factor, temperature, is known to be a significant driver of fish migration (Leggett 1997). In the Delaware estuary, the Atlantic sturgeon movement in the eastern portion was driven from warmer bottom temperatures along with other variables, such as depth. has been known to be driven by temperature (Breece 2018). As stated previously, it was found that the variable for Atlantic sturgeon presence in the DE WEA was bottom temperature, specifically between 10 - 25°C (Haulsee 2020).

Due to the Atlantic sturgeon migration toward the Delaware River occurring for spawning behavior, sex could be an important trait when considering occurrences in the DE WEA. Sex-based migratory behavior is seen in a number of species, including in different populations of Atlantic sturgeon. A population in the Hudson River is known to have a differentiation of sex during migratory periods. Males tend to arrive earlier in the year than females during the spawning season (Breece 2021). Studies have also shown male and female Atlantic sturgeon returning to their spawning grounds at different rates in New York rivers, with males returning at a higher rate than females (Hager 2020). It is not uncommon for the difference of sex to determine migrational behavior, thus sex was considered in this study as a testable ecological variable for this population of Atlantic sturgeon.

Photoperiod is another important ecological variable to consider when determining drivers of migration and occurrence. Photoperiod is the number of consecutive hours of daylight during a 24 hour period, also known as daylength (Runkle 2008). In the northern hemisphere, photoperiod is minimal during the first weeks after the winter solstice, then slowly increasing towards the summer solstice, then becoming minimal again in a repeated cycle. Timing stimuli, which includes photoperiod, has been known to be used by migratory fish. Through this term, photoperiod can be classified as a migratory signal, hence why it is hypothesized to be an ecological driver of sturgeon occurrences in the DE WEA (Smith 1985).

I created five hypotheses testing if photoperiod, bottom temperature or sturgeon sex had an effect on arrival or residency times. The hypotheses are stated below:

1. Male and Female Atlantic sturgeon have different (a) arrival times and (b) residence times in the DE WEA.
2. Bottom temperature predicts the arrival time of male and female Atlantic sturgeon.

3. Juvenile Atlantic sturgeon have a different (a) arrival time and (b) residence time than adult Atlantic sturgeon in the DE WEA.
4. Atlantic Sturgeon's river of origin influences (a) arrival time and (b) residence time in the DE WEA.
5. The Atlantic Sturgeon arrival time, based on river of origin, in the DE WEA is associated with the photoperiod.

Chapter 2

METHODS

2.1 The BOEM Study on Atlantic Sturgeon Occurrence

In the study done in the DE WEA by the University of Delaware and Delaware State University, fifty Atlantic sturgeon were tagged with VEMCO acoustic transmitters, with the focus towards mature adults. The tagging of the Atlantic sturgeon was done along the East Coast of the United States between April 2nd, 2017 - May 7th 2017 in a spread of 16 days, with 70 gill nets deployed. Sampling was done in compliance with the NOAA - NMFS permit #16507. These sturgeon were tagged using implantation protocols developed for Gulf sturgeon (*Acipenser oxyrinchus desotoi*) and were anaesthetized in a live well with 50- 125 mg l⁻¹ of tricaine methane sulfonate MS-222® (Fox et al 2000 and Damon-Randall et al. 2010). The live well ensured stable salinity, temperature, and dissolved oxygen levels from the sampling site during the tagging. During this procedure, photographs of the fish were taken along with other measurements: fork length, total length, weight, transmitter information, samples taken, place of origin, and any other information (e.g. unusual morphologies). If there was no prior PIT (Passive Integrated Transponder) tag found during a scan, one was inserted into the left side of the fish.

After the VEMCO transmitter was placed inside the sturgeon's abdomen, the fish was able to recover in a fresh seawater bin before being released. This is an invasive, yet necessary, process in order to implant the tag in the sturgeon.

In the DE WEA, there were 25 passive acoustic receivers arranged around the perimeter of the area (**Figure 2**). It should be noted there was no overlap with the range of detection for each of the receivers, they have an acoustic range of 1 km and were placed 3 km apart. Therefore, it was possible for fish to enter or vacate the array undetected. These receivers were maintained on a bi-monthly basis and were recovered between March 30th, 2018 and June 1st 2018. This meant there were two years of acoustic telemetry data collected, which was the data used for this senior thesis.

The data from the two year acoustic study was compiled along with the other variables taken as each sturgeon was detected. Among these Atlantic sturgeon detections, these receivers also detected other Atlantic sturgeon tagged from other studies done by other organizations. The variables collected for the 2020 report were thought to be factors that could indicate a driver of Atlantic sturgeon occurrence: yday (day of year), depth, surface sea temperature, bottom temperature, Wentworth sediment type, water absorption at 443 nm and 555 nm , and bottom slope. From this set of variables, conclusions were drawn that bottom temperature was the most ecological interpretation and driver towards Atlantic sturgeon occurrence when compared to the other variables.

2.2 The Senior Thesis Method

In the datasets collected, I matched each individual sturgeon with common ecological variables by their individual transmitter number using R. The following ecological variables were matched: sex, bottom temperature, river of origin, and photoperiod. For the variable

photoperiod, the package *meteor* was used to calculate the photoperiod over the course of a full calendar year.

When calculating the arrival and residency for each individual sturgeon, the package *dyplr* was also used in these calculations. For the arrival day, I took the minimum yday (day of year) each individual was detected in the DE WEA. This was labeled as the sturgeon first arrival day. For the residency time for each sturgeon, the length between minimum yday and maximum yday was calculated and labeled as the residence time for each sturgeon..

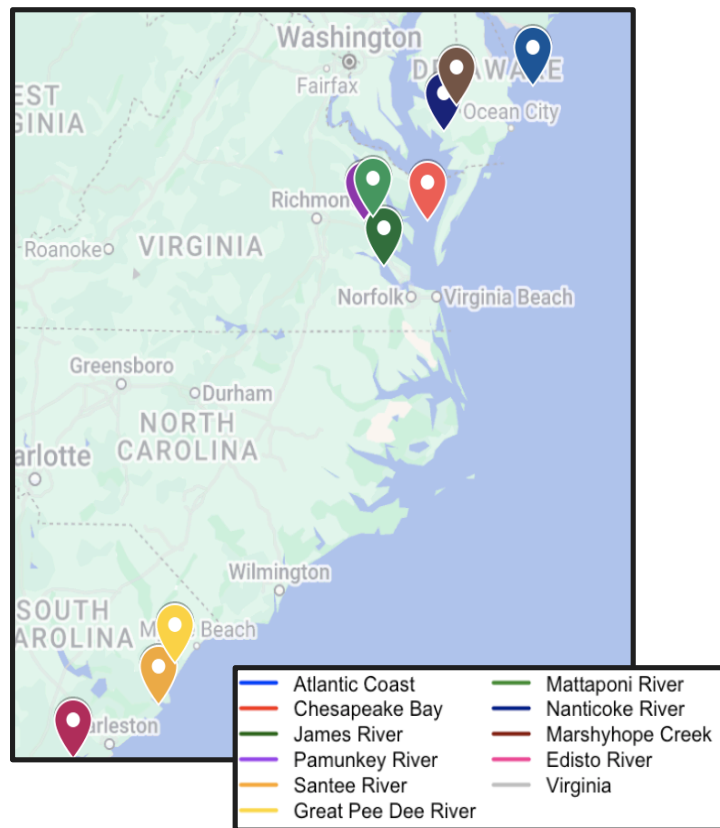


Figure 4. General Area of Release Location

General Area of Release location of the Atlantic sturgeon

I also tested if the tagging location of the sturgeon, otherwise known as the river of origin or release location, influenced arrival and residency. Within the dataset, there were twelve

tagging location locations recorded (**Figure 4**): Atlantic coast, Chesapeake Bay, James River, Pamunkey River, Santee River, Great Pee Dee River, Mattaponi River, Nanticoke River, Marshyhope Creek, Edisto River, NY/NJ Coast, and Virginia. When counting presences over the course of year by each release location, there was a total of 1,370 sturgeon detections within the DE WEA. Locations that were not rivers were removed from the data analysis. Then, the rivers that had fewer than ten sturgeon detections were also removed. Eight locations in total were removed for this thesis because they are not river specific: The Atlantic Coast (705 detections), Chesapeake Bay (216 detections), Pamunkey River (3 detections), Mattaponi River (3 detections), Nanticoke River (4 detections), Edisto River (9 detections), NY/NJ coast (205 detections), and Virginia (23 detections).

For the statistical analysis portion of this study, four statistical tests were used to test statistical significance: Kruskal Wallis test, Wilcoxon rank sum test, Watson Wheeler, and Dunn's test. The Kruskal Wallis, Watson Wheeler, Wilcoxon, and Dunn's tests are non-parametric tests, where they don't assume normal distribution. The Kruskal Wallis was done in hypotheses three, four, and five. Then, if statistical significance was found in order to find specific group differences, a Dunn's test was performed. Dunn's test was done through the package *FSA*. The Wilcoxon test was for hypotheses one and two, where sex was the main variable and was tested for the difference between male and female sturgeon groups. The Watson Wheeler test, which compares two or more samples, is meant for circular data. This test was done to determine any significant difference in arrival time across different groups. This statistical test was done through the package *circular*.

Chapter 3

RESULTS

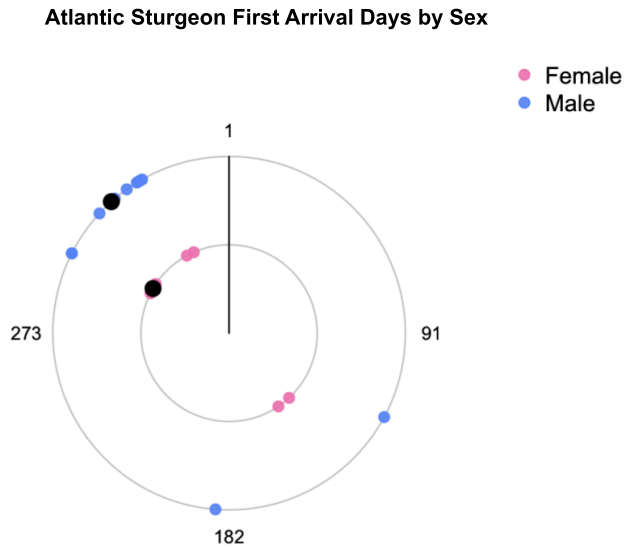


Figure 5: Circular Plot for day of arrival between female and male Atlantic sturgeon

A circular plot showing the distribution between male and female arrival during a year. Males are blue and females are pink. Used the packages *dyplr*, *stringer*, and *circular*. Median for females is 304.5 and the male median is 322.5. Watson Wheeler test used, p-value = 0.04609. Generated in R Studio and code aided by OpenAI.

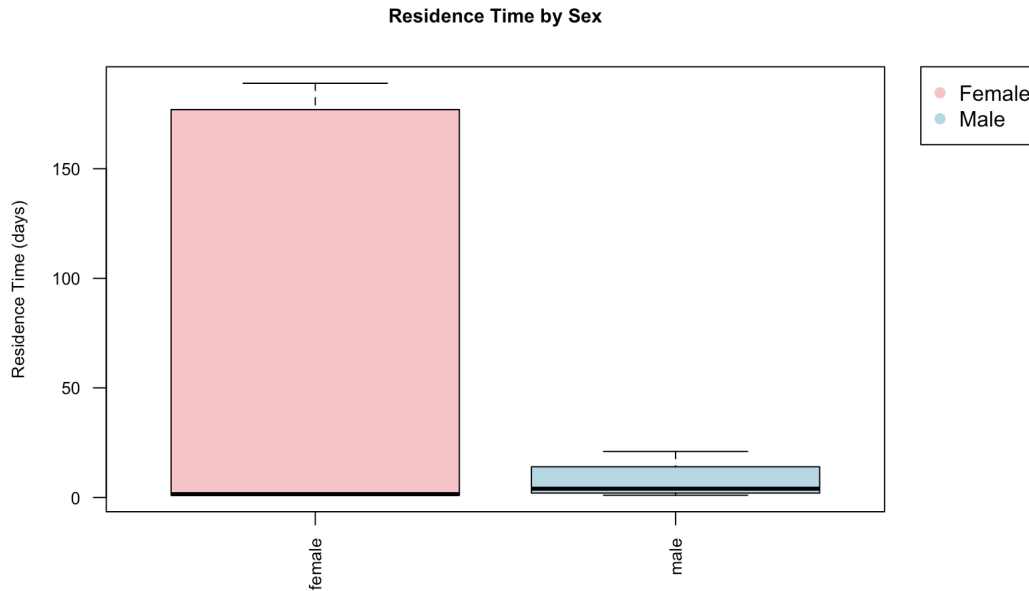


Figure 6: Boxplot of residency time between female and male Atlantic sturgeon

Each plot is colored by approximated sex of the Atlantic sturgeon recorded, female (pink) and blue (male). This boxplot shows the difference between male and female Atlantic sturgeon residency in the DE WEA. The females have a median of 150, with a minimum of 1 and a maximum of 189.00. The males have a lower median, 4.0, with a minimum of 1 and a maximum 21. The hypothesis tests for this part of hypothesis one showed statistical significance. Wilcoxon test was done, p-value = 0.7362. Used the packages *dplyr* and *stringer*. Generated in R Studio and code aided by OpenAI.

3.1 Hypothesis One - Arrival and Residence Times Between Male and Female Sturgeon

The first hypothesis tested was determining if male and female Atlantic sturgeon have different (a) arrival and (b) residence times within the DE WEA (**Figure 5** and **Figure 6**). A total of 20 sturgeon were used for their arrival and residence time, 6 female and 14 male. Two female sturgeon were removed from the dataset (Transmitter number ending in 16133 and 16148) for not having a bottom temperature recorded during the first day of arrival. The Watson Wheeler test rejected the null hypothesis for arrival times ($P = 0.04609$) ($P < 0.05$). For the residence Wilcoxon rank sum test, the null hypothesis failed to be rejected ($P = 0.7362$) ($P > 0.05$).

As seen in **Figure 5** and **Figure 6**, the spread of data for females in both plots is longer than the males. Female arrival has a minimum of day 139 to the maximum of day 341, an overall

range of 202. Female residency has a minimum of a 1 day residency to a maximum of 189 day residency, an overall range of 188 days. The male Atlantic sturgeon do have a larger range, with their arrival having a minimum of day 120 to the maximum of day 335, an overall range of 215. Male residency has a minimum of 1 day of residency to a maximum of 21 days of residency, an overall range of 20 days. However, if only discussing their arrival interquartile range (IQR), which removes the extremes seen in **Figure 5**, the IQR is 28 (1st quartile 301.0, 3rd quartile 329.0). The female's arrival IQR is 142.8 (1st quartile 148.0, 3rd quartile 336.0). This difference is also seen between the two sexes residency (**Figure 6**). Female Atlantic sturgeon have an IQR of 176 (1st quartile 1.00, 3rd quartile 177.0). Male Atlantic sturgeon have an IQR of 12 (1st quartile 2.00, 3rd quartile 14).

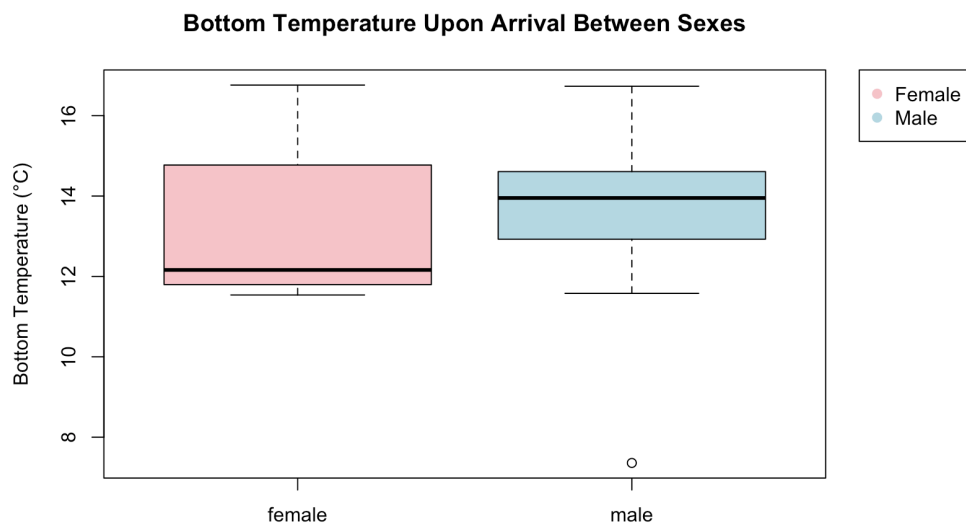


Figure 7: Boxplot of bottom temperature upon arrival between female and male Atlantic sturgeon

Each plot is colored by approximated sex of the Atlantic sturgeon recorded, female (pink) and blue (male). This boxplot shows the difference between male and female Atlantic sturgeon bottom temperature during their arrival in the DE WEA. The females had a median temperature of 12.16°C, with a minimum of 11.54°C and a maximum temperature of 16.76°C. The males had a median temperature of 13.95°C, with a minimum temperature of 11.58°C and a maximum 16.73°C. The Wilcoxon test was used for this hypothesis, p-value =0.2325. Generated in R Studio and code aided by OpenAI.

3.2 Hypothesis Two - Bottom Temperature with the Arrival of Male and

Female Sturgeon

The second hypothesis states bottom temperature predicts the arrival time of male and female sturgeon (**Figure 7**). The comparison of the first arrival temperature with the sex of the sturgeon was done through the same statistical tests as hypothesis one. The Wilcoxon test failed to reject the null hypothesis ($P = 0.2325$) ($P > 0.05$). The IQR of female bottom temperature is 2.61 (first quartile 11.80, third quartile 14.77). The male IQR for bottom temperature is 1.683 (first quartile 12.926, third quartile 14.609).

Atlantic Sturgeon First Arrival Days by Sex

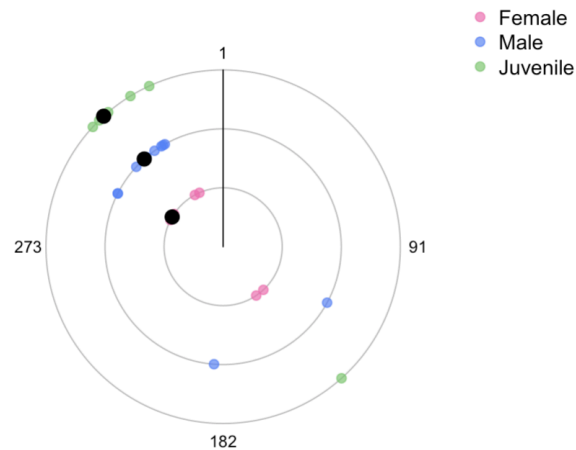


Figure 8: Circular plot of arrival between female, male, and unknown/juvenile Atlantic sturgeon

Each plot is colored by approximated sex of the Atlantic sturgeon recorded, female (pink), blue (male), and unknown/juvenile (green). The above plot shows the difference of arrival between female, male, and juvenile sturgeon in the DE WEA. The females and males have the medians as stated in **Hypothesis One**. The juveniles have a median of 322.0, with a minimum of 140.0 and a maximum of 340. Both male and juvenile sturgeon have outliers. The packages used are dyplr, stringer, and circular. The Watson Wheeler Test was used, $p\text{-value} = 0.187$. Generated in R Studio and code aided by OpenAI.

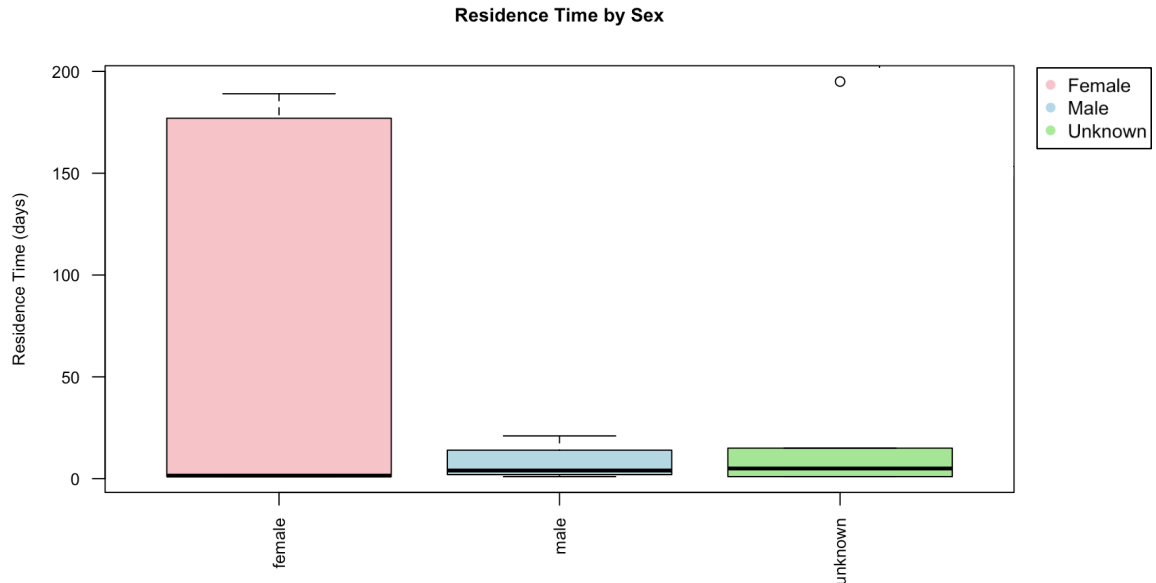


Figure 9: Boxplot of day of residency time between female, male, and unknown/juvenile Atlantic sturgeon

Each plot is colored by approximated sex of the Atlantic sturgeon recorded, female (pink), blue (male), and unknown/juvenile (green). The boxplot above shows the difference in residency between the sexes of Atlantic sturgeon in the DE WEA. The females have a median of 175.0, with a minimum of 1 and a maximum of 189.00. The males have a lower median, 4.0, with a minimum of 1.0 and a maximum of 21.0. The juvenile sturgeon have a median 5.0, with a minimum of 1.0 and a maximum of 195.0. The juvenile have outliers while the male and female do not. Packages used for this is *stringer* and *dypfr*. Kruskal Wallis test was used, $p\text{-value} = 0.9205$. Generated in R Studio and code aided by OpenAI.

3.3 Hypothesis Three - Arrival and Residence between Male, Female, and Juvenile

Sturgeon

To test the third hypothesis, I compared the arrival and residency between male, female, and juvenile Atlantic sturgeon in the DE WEA (**Figure 8** and **Figure 9**). Six juvenile Atlantic sturgeon were added to the adult data set, bringing the total sample size to 26 sturgeon. The third hypothesis states juvenile Atlantic sturgeon have a different (a) arrival time and (b) residence time than male and female Atlantic sturgeon in the DE WEA. The Watson Wheeler test for arrival failed to reject the null hypothesis ($P = 0.187$) ($P > 0.05$). For the residency data between the groups of sexes, the Kruskal-Wallis test performed failed to reject the null hypothesis ($P =$

0.954) ($P > 0.05$). The IQR of male and female arrival and residency is the same as hypothesis one. The arrival IQR for Juvenile sturgeon is 16 (first quartile 317, third quartile is 333). The residency IQR is 14 (first quartile 1, third quartile is 15).

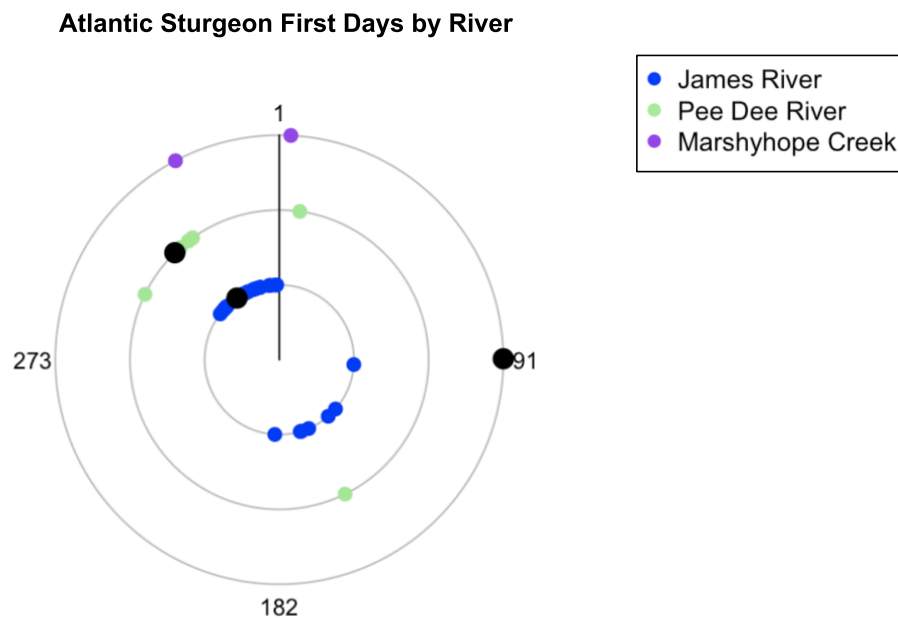


Figure 10: Circular plot of arrival between different release locations

Each plot is colored by specific release locations. The boxplot above is the difference in arrival of Atlantic sturgeon from different release locations. The James River sturgeon has a median of 330.0, with a minimum of 95 and maximum of 363. The Great Pee Dee River sturgeons had a median of 320, a maximum of 329 and minimum of 8. The Marshyhope Creek had a median of 91, with a maximum of 337 and a minimum of 3. The packages *dyplr*, *lubridate*, *stringr*, *tidyr*, *forcats*, *circular*. Watson Wheeler was performed on this hypothesis, $p\text{-value} = 0.08592$. Generated in R Studio and code aided by OpenAI.

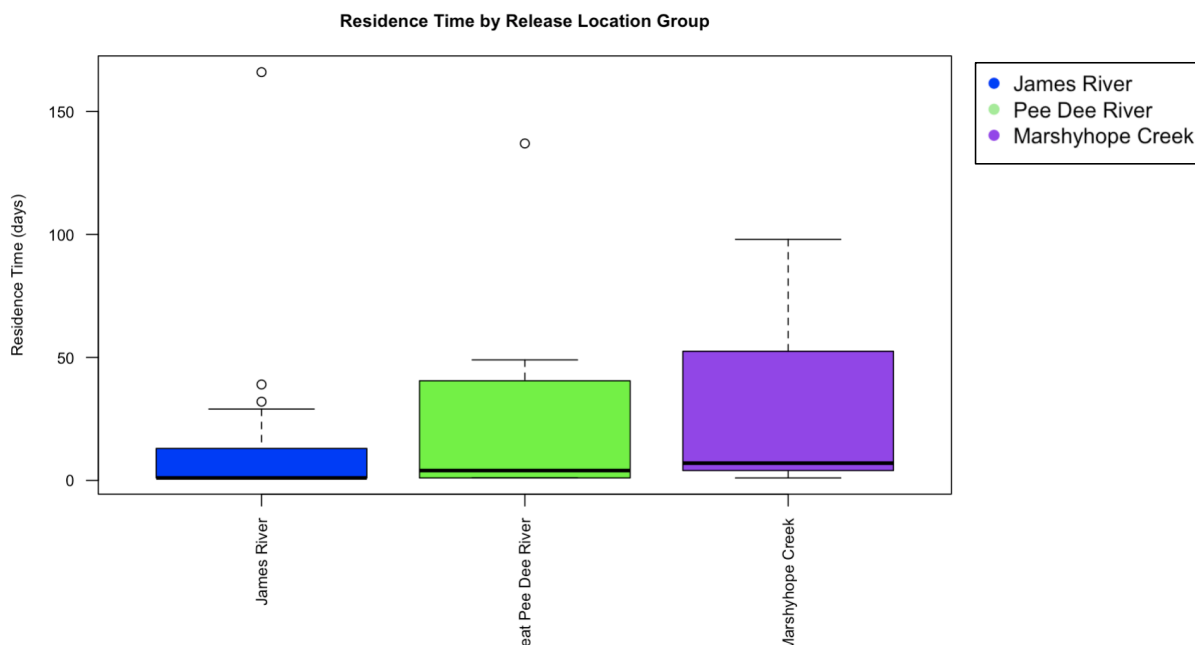


Figure 11: Boxplot of residence times between different release locations

Each plot is colored by specific release locations. The figure above is a boxplots that shows the residency times between the different release locations. The James River had a median of 1, with a minimum of 1, and a maximum of 166 (outlier). The Great Pee Dee River had a median of 4, a maximum of 137, and a minimum 1. The James River and the Great Pee Dee River exhibited outliers. The Marshyhope Creek had a median of 7, a maximum of 98, and a minimum of 1. The packages *dyplr*, *lubridate*, *stringr*, *tidyr*, *forcats*, *circular*. A Kruskal Wallis was performed on this hypothesis, p-value = 0.5387. Generated in R Studio and code aided by OpenAI.

3.4 Hypothesis Four - Arrival and Residence Time of the Sturgeon's River of Origin

Hypothesis four states, Atlantic sturgeon's river of origin influences (a) arrival time and (b) residence time in the DE WEA (**Figure 11 and Figure 12**). Again, the populations removed from the study were sturgeon from rivers or locations that had less than ten detections. This leaves the James River (134 detections), Santee River (17 detections), Great Pee Dee River (36), and the Marshyhope Creek (15 detections). The Santee River only had a single sturgeon detected, so it was removed from further data analysis.

For hypothesis four, 47 Atlantic sturgeon were detected in the DE WEA based on their release location group. The Watson Wheeler test failed to reject the null hypothesis ($P = 0.08592$) ($P > 0.05$). For the residency part of hypothesis four, the same 47 sturgeon were tested for their time spent in the DE WEA. When the Kruskal Wallis test was performed, the null hypothesis failed to be rejected ($P = 0.5387$) ($P > 0.05$).

For arrival, the James River has an IQR of 26 (1st quartile 316.0, 3rd quartile 342.0). Santee River has an IQR of 0, since there was only one sturgeon overall occurring with a total of 17 detections. The Great Pee Dee River has an IQR of 97 (1st quartile 228, 3rd quartile 325.0). Finally, Marshyhope Creek has an IQR of 167 (1st quartile 47.0, 3rd quartile 214.0). By not including the extremes, there are differences in arrival time between each tagging location. As for residency time in the DE WEA, the James river has an IQR of 12 (1st quartile 1.0, 3rd quartile 13.0). The Great Pee Dee River has an IQR of 39.5 (1st quartile 1.0, 3rd quartile 40.5). Finally, the Marshyhope Creek has an IQR of 48.5 (1st quartile 4.0, 3rd quartile 52.50).

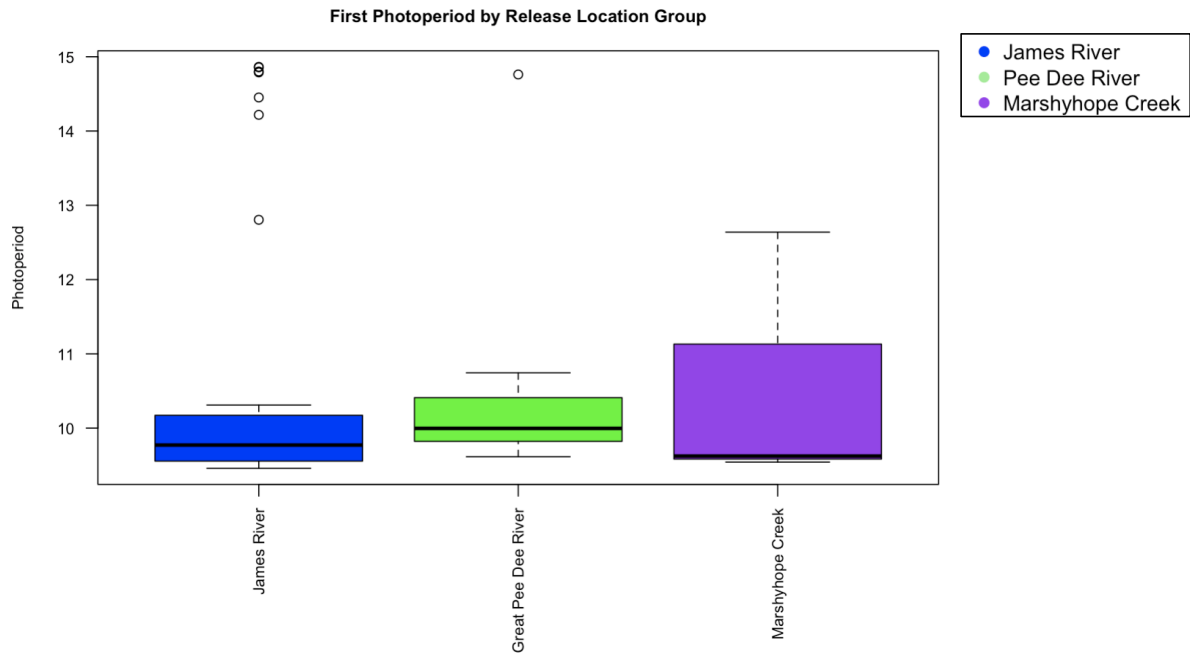


Figure 12: Boxplot of first photoperiod upon arrival by different release locations

Each plot is colored by specific release locations. Above is a boxplot showing the difference in photoperiod upon specific release locations groups. The James river had a median of 9.772, with a maximum of 10.310 and a minimum of 9.458. The Santee River had one sturgeon, so the median, maximum, and minimum were all 12.99. The Great Pee Dee River had a median of 9.997, a maximum of 10.745 and a minimum of 9.615. The Marshyhope Creek had a median of 9.624, with a maximum of 12.638 and a minimum of 9.543. The packages for this code were *dplyr*, *meteor*, and *circular*. A Kruskal Wallis was performed on this hypothesis, p-value = 0.4963. Generated in R Studio and code aided by OpenAI.

3.5 Hypothesis Five - Photoperiod with The Arrival of Each River of Origin

For hypothesis five, the Atlantic Sturgeon arrival time based on river of origin is associated with the photoperiod (**Figure 13**). This meant the same 4 release locations and 47 sturgeon tested in hypothesis four. The Kruskal Wallis test failed to reject the null hypothesis ($P = 0.4963$) ($P > 0.05$). The James River had an IQR of 0.617 (1st quartile 9.555, 3rd quartile 10.172). The Great Pee Dee River had an IQR of 0.409 (1st quartile 9.821, 3rd quartile 10.410). Finally, Marshyhope Creek had an IQR of 1.548 (1st quartile 9.583, 3rd quartile 11.131).

Chapter Four

DISCUSSION

Research on Atlantic sturgeon in the DE WEA is necessary to help conserve and aid their population recovery. These endangered individuals' movement in Delaware waters is how the construction of the DE WEA could threaten their existence. This thesis provides indications on how to better understand their movement ecology, specifically ecological drivers for their arrival and residency. Analyzing the data from the 2020 report done by Delaware State University and the University of Delaware provided grounds to create this thesis and find testable variables. The findings of Dr. Haulsee and team researched the occurrences of these Atlantic sturgeon, while this thesis specifically focused on individuals' arrival and residency time in the DE WEA. Clean energy is needed in the 21st Century, and the Mid-Atlantic Bight has great offshore wind energy potential. The promotion of Atlantic sturgeon conservation is not an argument against the DE WEA, it's an identifiable problem that could occur during construction. Finding an appropriate time frame to mitigate and limit sturgeon harm is necessary and in the best interest towards the institutions and organizations involved within this project.

Researching the occurrence of the Atlantic sturgeon is not enough to fully understand the population's movement. Their arrival and residency times in the DE WEA provides researchers with a specific movement pattern. Knowing the arrival and residency of the Atlantic sturgeon is beneficial because it provides a time frame of possible months to avoid, pause, or start construction. Through the five hypotheses, four main ecological variables were tested: sex, river of origin, bottom temperature, and photoperiod. Through multiple statistical tests, I found that sex is the best ecological variable for sturgeon arrival time. Essentially, female and male Atlantic sturgeon individuals arrive at different times in the DE WEA (Day 304 vs. Day 322), an internal

factor which dictates their movement ecology. This significance can further help other studies, organizations, and institutions better understand the migratory behavior of the Atlantic sturgeon. The second part of hypothesis one, which focused on residency by sex, did not find statistical significance.

As described above, even if the statistical tests did not deem the difference between male and female sturgeon residency to be statistically significant, female Atlantic sturgeon individuals have longer exposure to the DE WEA than the males. The residency IQR for females is much longer than males (176 days vs. 12 days). This has the potential to be hazardous to the females during the time of construction. If female Atlantic sturgeon tend to arrive early, and have a longer period of residency, they are more at risk to interact with construction. Females are also the ones who reproduce and provide new sturgeon to the already depleted population. Using sex to describe their arrival and residence behavior can help researchers and organizations alleviate consequences.

For this study, the variable of the capture and release location of the sturgeon was considered for the Atlantic sturgeon's arrival and residency in the DE WEA. Overall, 47 sturgeon were used from four different release locations: the James River, the Santee River, the Great Pee Dee River, and the Marshyhope Creek. From hypothesis four results, there was no statistical significance between each of these locations. We cannot conclude that the release location is a driver of Atlantic sturgeon arrival or residency in the DE WEA. However, just as the issue from hypothesis one, the release locations studied for hypothesis four have different arrival and residency IQRs (**Figure 11** and **Figure 12**). The difference amongst these four tagging locations is prominent, however some of the population size for each location used for these calculations and statistical tests is small. The Santee River had the smallest population, with only a single

sturgeon. The Mashhope river had 3 sturgeon, the Great Pee Dee River had 8, and the James River had 35 individual sturgeon.

The individual sturgeon used for the release locations were also used in hypothesis five, which focused on photoperiod. This also did not show any statistical significance, however, this could be also due to the small populations being used. The differences in IQR were not as severe as hypothesis four, however, Marshhope Creek had the largest arrival and residency IQR (167 and 48.5), this is over twice as large as the IQR of the James River and the Great Pee Dee River. This could signify that the small populations in the used release locations are too small for accurate statistical analysis.

Hudson River Atlantic sturgeon have also been found to differentiate by sex in their migration, with males occurring earlier in the year than females (Breece 2021). However, in this thesis, the females arrived in the DE WEA earlier in the year, having a median day of about 304 (late October). While the males arrived later and had a median arrival on day 322 (mid November). This arrival time indicates movement near the Delaware Bay, which agrees with past studies showing that Atlantic sturgeon are known to aggregate in the mouth of estuaries in the fall (Haulsee 2020). It is important to account for this finding, due to there being a sex dependent differentiation in behavior. Nevertheless, the focus of this study is on the DE WEA area and the sturgeon in this wind farm area. Companies and organizations involved with the construction of the DE WEA should utilize this thesis to consider another ecological variable, sex, for the arrival of Atlantic sturgeon in the Delaware waters, specifically the DE WEA.

Based on the 2020 BOEM report, the Atlantic sturgeon was concluded to have bottom temperature as an environmental predictor variable for their occurrence in the DE WEA. This thesis argues that sex is an ecological driver of their arrival in the DE WEA. This provides detail

on not only when Atlantic sturgeon are in the area, but the intraspecific information about these sturgeon (male vs. female). Construction should be planned around when these females will be arriving, especially if these sturgeon are aggregating in the mouth of the Delaware Bay in the fall. Based on these results, construction of the DE WEA should take place primarily in the summer months. This statement also agrees with the findings and suggestions in the 2020 BOEM reports.

The conclusion of bottom temperature being an indicator variable for the Atlantic sturgeon arrival should be further researched. In the Delaware Bay, stratification happens on a seasonal basis. In the summer, the sun warms the upper layer and stratification is strengthened. Then, when it becomes cold again, the water becomes well mixed. Bottom temperatures and surface temperatures tend to be similar or the same during sturgeon arrival, hence, when the water column is more well-mixed (**Figure 3**). Future research could indicate if the Atlantic sturgeon arrival is based on how well- mixed the water column is. Perhaps bottom temperature is only a piece, while stratification is the picture.

Another perspective towards the Atlantic sturgeon conservation is towards its organismal biology. Atlantic sturgeon have electrosensory organs (VIMS). If there are electrical currents happening in and around the DE WEA, the Atlantic sturgeons could be disoriented from this additional environmental condition. More research will have to be done to conclude the effect of the electrical currents within the DE WEA on Atlantic sturgeon.

Chapter Five

CONCLUSION

When finding if an ecological variable could indicate or drive the arrival and residency of a species in a specific area, a large population is needed to reduce variability and strengthen statistical tests. For this thesis, large populations of the data sets were not prominent for all hypotheses, which affects the statistical analysis portion. In fact, during the Watson Wheeler test, it was noted some p-values may be unreliable due to some groups having less than 10 elements. The elements being referred to the amount of sturgeon in each “group” (i.e. female sturgeon = 6). This was not an error in the data sampling from the initial study, but a limitation. Atlantic sturgeon are a difficult species to sex, requiring an invasive and stressful procedure. Simply, a limitation in this thesis is the increased likelihood of a type II error. This is where the null hypothesis failed to be rejected, when in reality, the alternative hypothesis is true.

This data is limited to Atlantic sturgeon occurring only in Delaware waters. Other populations are needed to have Atlantic sturgeon behavior properly researched. The range and overall spread of the data between male and females also suggests limitations that could lead to false negatives. The results from hypothesis one were the only results able to reject the null hypothesis. The sex of Atlantic sturgeon should now be considered as an ecological variable and driver when discussing sturgeon arrival and residency time in the DE WEA. Furthermore, this variable should be applied and considered to other offshore wind energy projects on the East Coast if Atlantic sturgeon are found in the area of construction.

References

- Alison Mitchell. *Last call for unique Delaware River Atlantic sturgeon - New Jersey Conservation Foundation*. (2025, July 10). New Jersey Conservation Foundation.
<https://www.njconservation.org/atlantic-sturgeon/>
- Atlantic States Marine Fisheries Commission. (2012). *HABITAT ADDENDUM IV TO AMENDMENT 1 TO THE INTERSTATE FISHERY MANAGEMENT PLAN FOR ATLANTIC STURGEON*.
https://asmfc.org/wp-content/uploads/2025/01/sturgeonHabitatAddendumIV_Sept2012.pdf
- Bemis, W. E., & Kynard, B. (1997). Sturgeon rivers: an introduction to acipenseriform biogeography and life history. *Environmental Biology of Fishes*, 48(1–4), 167–183.
<https://doi.org/10.1023/a:1007312524792>
- Breece, M. W., Oliver, M. J., Cimino, M. A., & Fox, D. A. (2013). Shifting distributions of adult Atlantic sturgeon amidst post-industrialization and future impacts in the Delaware River: A maximum entropy approach. *PLoS ONE*, 8(11).
<https://doi.org/10.1371/journal.pone.0081321>
- Breece, M., Fox, D., Dunton, K., Frisk, M., Jordaan, A., & Oliver, M. (2016). Dynamic seascapes predict the marine occurrence of an endangered species: Atlantic sturgeon *Acipenser Oxyrinchus oxyrinchus*. *Methods in Ecology and Evolution*, 7(6), 725–733.
- Breece, M. W., Fox, D. A., & Oliver, M. J. (2018). Environmental drivers of adult Atlantic Sturgeon movement and residency in the Delaware Bay. *Marine and Coastal Fisheries*, 10(2), 269–280. <https://doi.org/10.1002/mcf2.10025>

OpenAI. (2024, 2025, 2026). *ChatGPT*

<https://chat.openai.com>

Collins, M. R., J., Rogers, S. G., Smith, T. L., & Moser, M. L. (2000). PRIMARY FACTORS AFFECTING STURGEON POPULATIONS IN THE SOUTHEASTERN UNITED STATES: FISHING MORTALITY AND DEGRADATION OF ESSENTIAL HABITATS. In *BULLETIN OF MARINE SCIENCE* (Vol. 66, Issue 3, pp. 917–928).

https://www.webapps.nwfsc.noaa.gov/assets/2/9238_09252017_124430_Collins.et.al.2000-Bull-Mar-Sci-66-3-Moser.pdf

Daigle, N. J., White, S., Lubinski, B. A., Johnson, R., Kazyak, D. C., Verhille, C. E., Gillis, C. A., & Sacobie, C. F. D. (2025). Stock composition of cryptic Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) in the Restigouche River and estuary, Canada. *Scientific Reports*, 15(1), 20654. <https://doi.org/10.1038/s41598-025-04551-x>

Damon-Randall, K., Bohl, R., Bolden, S., Fox, D., Hager, C., Hickson, B., Hilton, E., Mohler, J., Robbins, E., Savoy, T., & Spells, A. (2010). Atlantic Sturgeon Research Techniques. *NOAA*. <https://repository.library.noaa.gov/view/noaa/3731>

Delaware's Endangered Species - DNREC. (2025, April 28). DNREC.

<https://dnrec.delaware.gov/fish-wildlife/conservation/endangered-species/>

Erickson, D. L., et al. “Use of Pop-up Satellite Archival Tags to Identify Oceanic-Migratory Patterns for Adult Atlantic Sturgeon, *Acipenser Oxyrinchus Oxyrinchus* Mitchell, 1815.” *Journal of Applied Ichthyology*, vol. 27, no. 2, 28 Mar. 2011, pp. 356–365, <https://doi.org/10.1111/j.1439-0426.2011.01690.x>. Accessed 11 Nov. 2021.

Exploring Ocean Acoustics: Active vs. Passive Techniques. (2024, May 15). Sinay.

<https://sinay.ai/en/what-is-the-difference-between-active-and-passive-acoustic/>

Fisheries, N. (2024, May 31). *Atlantic Sturgeon*. NOAA.

<https://www.fisheries.noaa.gov/species/atlantic-sturgeon>

Fox, D. A., Hightower, J. E., & Parauka, F. M. (2000). Gulf Sturgeon spawning migration and habitat in the Choctawhatchee River System, Alabama–Florida. *Transactions of the American Fisheries Society*, 129(3), 811–826.

[https://doi.org/10.1577/1548-8659\(2000\)129](https://doi.org/10.1577/1548-8659(2000)129)

Hager, C. H., Watterson, J. C., & Kahn, J. E. (2020). Spawning drivers and frequency of endangered Atlantic sturgeon in the York River system. *Transactions of the American Fisheries Society*, 149(4), 474–485. <https://doi.org/10.1002/tafs.10241>

Haulsee, Danielle , et al. *Occurrence of Commercially Important and Endangered Fishes in Delaware Wind Energy Areas Using Acoustic Telemetry*. Jan. 2020.

Laney, R. W., Atlantic, S., Hightower, J. E., Versak, B. R., Angold, M. F. M., & Ole, W. W. C. (2007). Distribution, Habitat Use, and Size of Atlantic Sturgeon Captured during Cooperative Winter Tagging Cruises, 1988-2006. *American Fisheries Society Symposium*. <http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.507.21>

Leggett, W. (1997). The Ecology of Fish Migrations. *Annual Review of Ecology and Systematics*, 8. <https://www.jstor.org/stable/2096730>

Life in the Slow Lane: Ecology and Conservation of Long-Lived Marine Animals. (1999). In *American Fisheries Society eBooks*. <https://doi.org/10.47886/9781888569155.ch16>

Limburg, K. E., & Waldman, J. R. (2009). Dramatic declines in North Atlantic diadromous fishes. *BioScience*, 59(11), 955–965. <https://doi.org/10.1525/bio.2009.59.11.7>

Matthew W Breece, Dewayne A Fox, Danielle E Haulsee, Isaac I Wirgin, Matthew J Oliver, Satellite driven distribution models of endangered Atlantic sturgeon occurrence in the

- mid-Atlantic Bight, *ICES Journal of Marine Science*, Volume 75, Issue 2, March-April 2018, Pages 562–571, <https://doi.org/10.1093/icesjms/fsx187>
- Matthew W. Breece, Dewayne A. Fox, Matthew J. Oliver, Environmental Drivers of Adult Atlantic Sturgeon Movement and Residency in the Delaware Bay, *Marine and Coastal Fisheries*, Volume 10, Issue 2, April 2018, Pages 269–280, <https://doi.org/10.1002/mcf2.10025>
- Musial, W., & Ram, B. (2010). *Large-Scale Offshore wind power in the United States: Assessment of Opportunities and Barriers*. <https://doi.org/10.2172/990101>
- Nathan, R., et al. “A Movement Ecology Paradigm for Unifying Organismal Movement Research.” *Proceedings of the National Academy of Sciences*, vol. 105, no. 49, 5 Dec. 2008, pp. 19052–19059, <https://doi.org/10.1073/pnas.0800375105>.
- Report Atlantic Sturgeon - DNREC*. (2024, August 27). DNREC. <https://dnrec.delaware.gov/fish-wildlife/fishing/sturgeon/>
- Oliver, M. J., Breece, M. W., Fox, D. A., Haulsee, D. E., Kohut, J. T., Manderson, J., & Savoy, T. (2013). Shrinking the Haystack: Using an AUV in an Integrated Ocean Observatory to Map Atlantic Sturgeon in the Coastal Ocean. *Fisheries*, 38(5), 210–216. <https://doi.org/10.1080/03632415.2013.782861>
- Rothermel, E. R., Balazik, M. T., Best, J. E., Breece, M. W., Fox, D. A., Gahagan, B. I., Haulsee, D. E., Higgs, A. L., O’Brien, M. H., Oliver, M. J., Park, I. A., & Secor, D. H. (2020). Comparative migration ecology of Striped Bass and Atlantic sturgeon in the US Southern mid-Atlantic bight flyway. *PLOS ONE*, 15(6). <https://doi.org/10.1371/journal.pone.0234442>

- Runkle, E. & GPN. (2008). Understanding your location's natural photoperiod will help determine the most economical strategy for providing long days when needed. In *GPN*. <https://www.canr.msu.edu/uploads/resources/pdfs/whatisyourphotoperiod.pdf>
- Scales, K. L., Hazen, E. L., Jacox, M. G., Edwards, C. A., Boustany, A. M., Oliver, M. J., & Bograd, S. J. (2016a). Scale of inference: On the sensitivity of habitat models for wide-ranging marine predators to the resolution of Environmental Data. *Ecography*, 40(1), 210–220. <https://doi.org/10.1111/ecog.02272>
- Shaw, A. K. (2016). Drivers of animal migration and implications in changing environments. *Evolutionary Ecology*, 30(6), 991–1007. <https://doi.org/10.1007/s10682-016-9860-5>
- Smith, R. J. F. (1985). The control of fish migration. In *Zoophysiology*. <https://doi.org/10.1007/978-3-642-82348-0>
- Smith, T. I. J. (1985a). The fishery, biology, and management of Atlantic sturgeon, *Acipenser oxyrinchus*, in North America. *Environmental Biology of Fishes*, 14(1), 61–72. <https://doi.org/10.1007/bf00001577>
- Smith, T. I. J. (1985b). The fishery, biology, and management of Atlantic sturgeon, *Acipenser oxyrinchus*, in North America. *Environmental Biology of Fishes*, 14(1), 61–72. <https://doi.org/10.1007/bf00001577>
- Sullivan, J. K. (1994). Habitat status and trends in the Delaware Estuary. *Coastal Management*, 22(1), 49–79. <https://doi.org/10.1080/08920759409362218>
- The Ecology of Fish Migrations. (1997). *Annual Review of Ecology and Systematics*, 8, 285–308. <http://www.jstor.org/stable/2096730>
- “U.S. Energy Information Administration (EIA) - Electricity.” *Eia.gov*, 2016, www.eia.gov/electricity/.